# Technological Innovation for Achieving SI-traceable Infrared Radiance Measurements for CLARREO

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## Introduction

Satellite measurements pinned to international standards are needed to monitor the Earth's climate, quantify human influence thereon, and test forecasts of future climate change[1-4]. Credible observations require that measurement uncertainties be evaluated on-orbit, during a mission's operational lifetime. The most accurate spaceborne measurements of thermal infrared radiance are achieved with blackbody calibration. The physical properties of blackbody cavity surface coatings, temperature probes and readout electronics are known to change upon extended exposure to the low-Earth orbit environment. Any such drift must be quantified in order to continue correctly calibrating observed radiance on-orbit.

The spectral radiance $B_{\tilde{\nu}}(T)$ emitted by a blackbody cavity of uniform temperature $T$ with an infinitesimal aperture is described by the Planck function

$$B_{\tilde{\nu}}(T) = \frac{2hc^2\tilde{\nu}^3}{\exp(\frac{hc\tilde{\nu}}{k_B T})-1},$$

where $h$ is Planck's constant, $c$ is the speed of light in a vacuum, $k_B$ is the Boltzmann constant and $\tilde{\nu}$ is the spectral index in cm$^{-1}$. The spectral radiance $I_{\tilde{\nu}}$ emitted by a cavity with a finite aperture with Lambertian reflectance is

$$I_{\tilde{\nu}} = \varepsilon_{\tilde{\nu}} B_{\tilde{\nu}}(T) + (1-\varepsilon_{\tilde{\nu}}) B_{\tilde{\nu}}(T^{\mathrm{eff}}),$$

where $\varepsilon_{\tilde{\nu}}$ is the cavity emissivity, and $T^{\mathrm{eff}}$ is the effective temperature of the radiation from the background environment assuming that it is spatially isotropic and isothermal. The dominant source of uncertainty in a well-designed blackbody arises from the measurement of the cavity temperature and the effect of the nonunity emissivity of a practical macroscopic blackbody aperture. Demonstration of an SI-traceable infrared radiance scale requires that the uncertainty in both blackbody temperature and emissivity measurement be known on-orbit. We present novel experimental designs that meet these requirements and are compact and transferable to an Earth observing satellite platforms[5,6].

## Technological Innovation for On-orbit Temperature Measurement

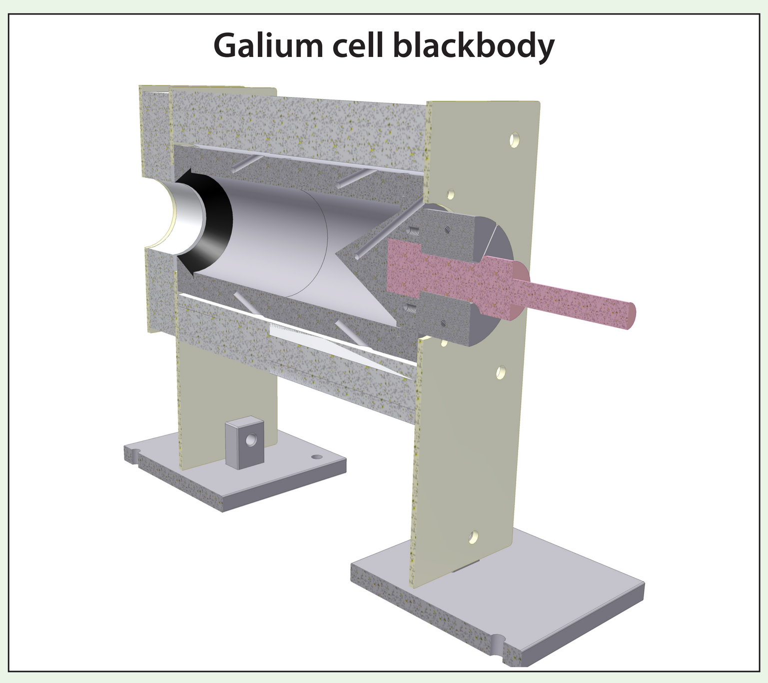



**Fig. 1.** A gallium melting point standard, consisting of 25 g of high-purity gallium in a chemically stable sealed crucible, allows the realization of the gallium melting point at 29.7646 ± 0.0007°C, which is a defining point of the ITS-90 temperature scale. The melting point standard is thermally integrated to be near the primary emitting surface of a laboratory blackbody. A thermal model allows the temperature of the gallium during the phase change to be related to the temperature probes in various locations in the blackbody.

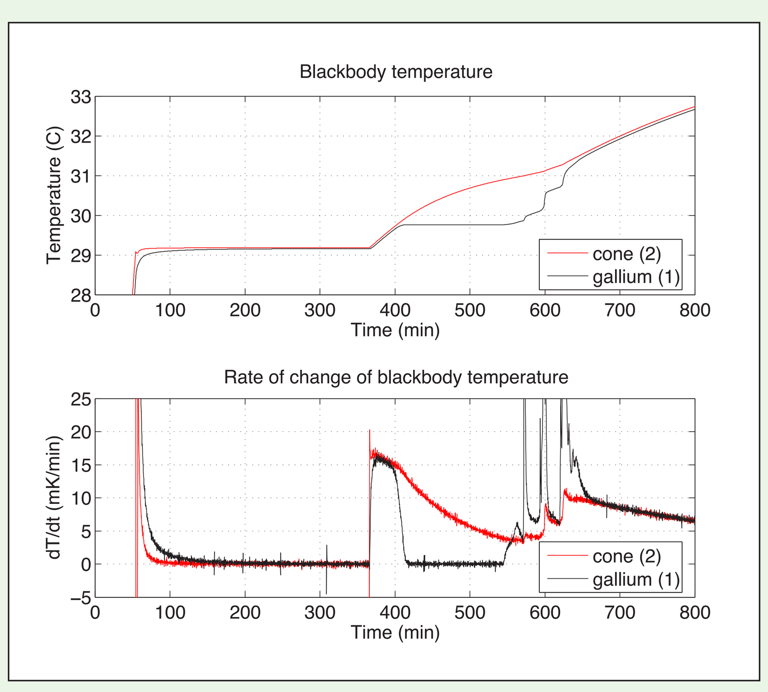



**Fig. 2.** A full melting transition of the gallium cell blackbody is achieved by applying constant power to slowly heat the blackbody from below to above the gallium melting point. The top panel shows the temperature of the blackbody primary emitting surface (cone, red curve) and the gallium (black curve) during the melt. The gallium melting point was reached around time index 410 min, at which point the temperature inside the cell remained constant for the next 120 mins. The onset of the melting point can be identified with an accuracy of 5 mK[5,7]. After the melt, the temperature of the cell reequilibrated with the rest of the blackbody. The bottom panel shows the rate of change of temperature for the blackbody cone and the gallium.

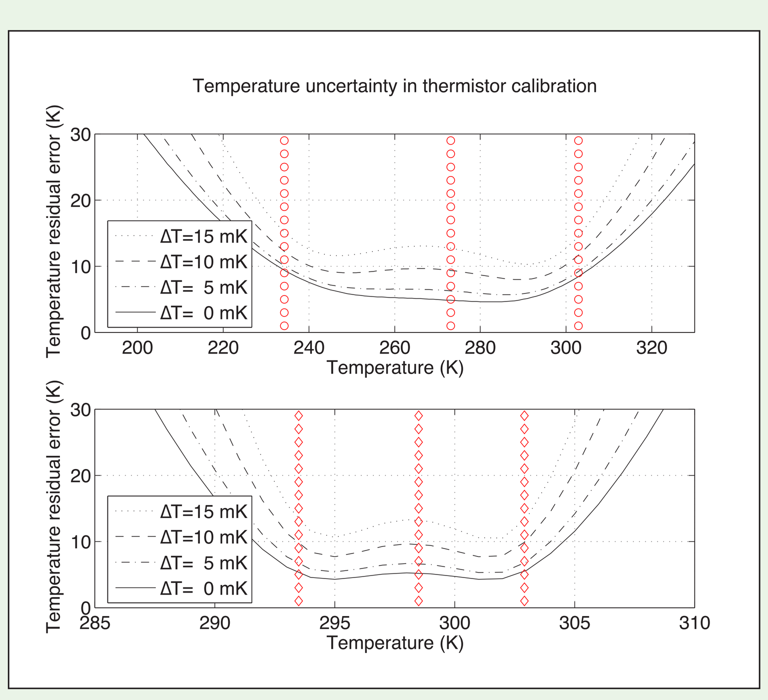



**Fig. 3.** By using multiple phase change standards, temperature probes may be directly calibrated on-orbit across a range of temperatures. The top panel shows the combined uncertainty from temperature measurement and electronics in calibrating a 10 kΩ thermistor using the fixed points of Hg, $H_2O$ and Ga (indicated by the red vertical lines of symbols). The bottom panel shows the uncertainty for a 30 kΩ thermistor calibrated at the fixed points of GaSn, GaZn and Ga. The results indicate that within the region bounded by the phase-change temperatures, the combined thermometric uncertainty is dominated by the uncertainty in the phase-change temperature determination. This shows that that it is possible to calibrate temperature probes on-orbit with adequately low uncertainties to meet the demands of climate observations.

Condensed from Gero, P. J., J. A. Dykema, and J. G. Anderson, 2008: A blackbody design for SI-traceable radiometry for Earth observation. *J. Atmos. Oceanic Technol.*, **25**, 2046–54.

## Technological Innovation for On-orbit Materials Characterization

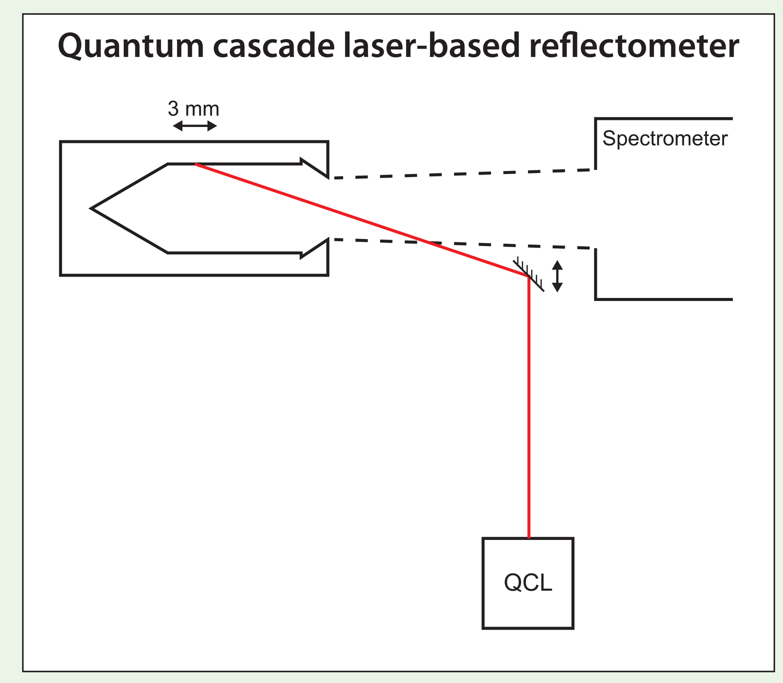



**Fig. 4.** A quantum cascade laser (QCL-based) reflectometer was used to monitor changes in blackbody emissivity. The QCL is a solid-state laser that can operate in continuous-wave mode at thermo-electrically cooled temperatures. The laser beam (7.91 μm, 38 mW, single mode) is free-space coupled into a laboratory blackbody. The attenuated reflected radiation is measured with an infrared spectrometer system, comprised of calibration blackbodies, an interferometer and detectors.

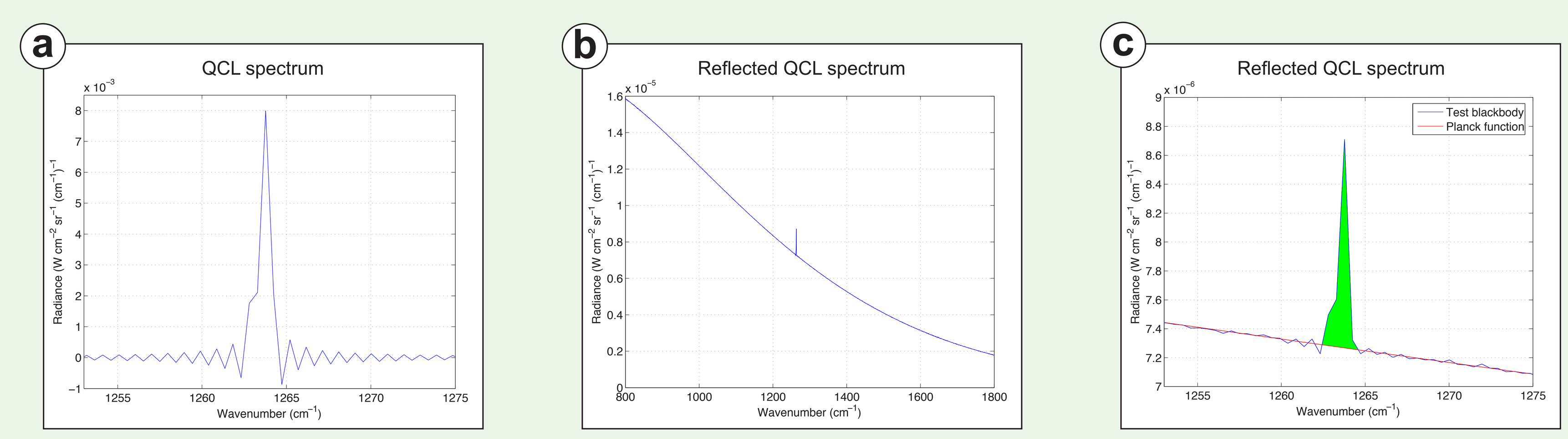



**Fig. 5.** (a) Spectrum of the quantum cascade laser observed with a Fourier transform spectrometer at 0.5 cm$^{-1}$ resolution (unapodized). (b) Spectrum of a blackbody and the reflected QCL radiation, as observed by the spectrometer, showing the sharp laser peak superimposed on the baseline Planck blackbody radiation. (c) Expanded view of the laser peak in (b) (blue curve). Using a fit to the baseline Planck function (red curve), the reflected laser radiance can be calculated (shaded in green). By taking the ratio between the reflected laser radiance and the incident laser radiance, the laser reflectivity can be obtained, which can be related to the cavity effective emissivity[6,8].

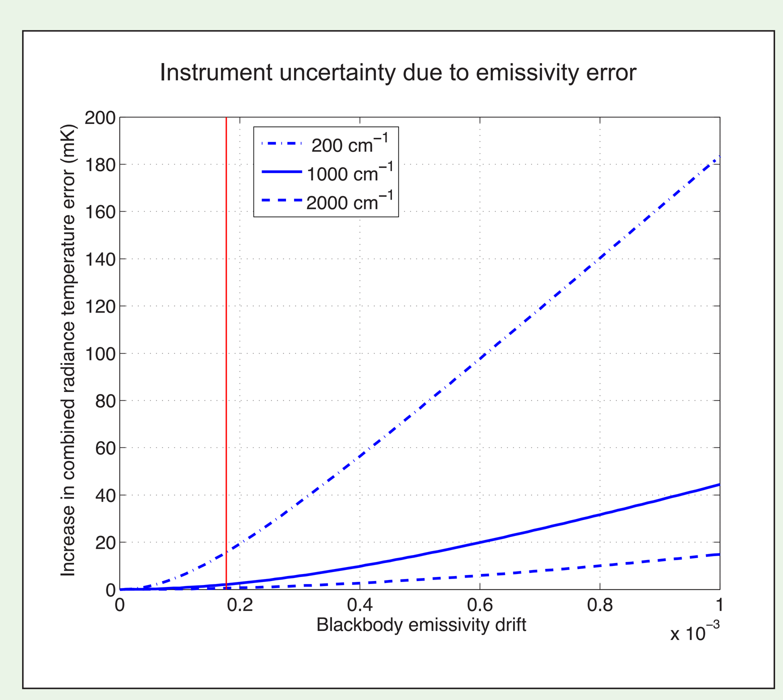
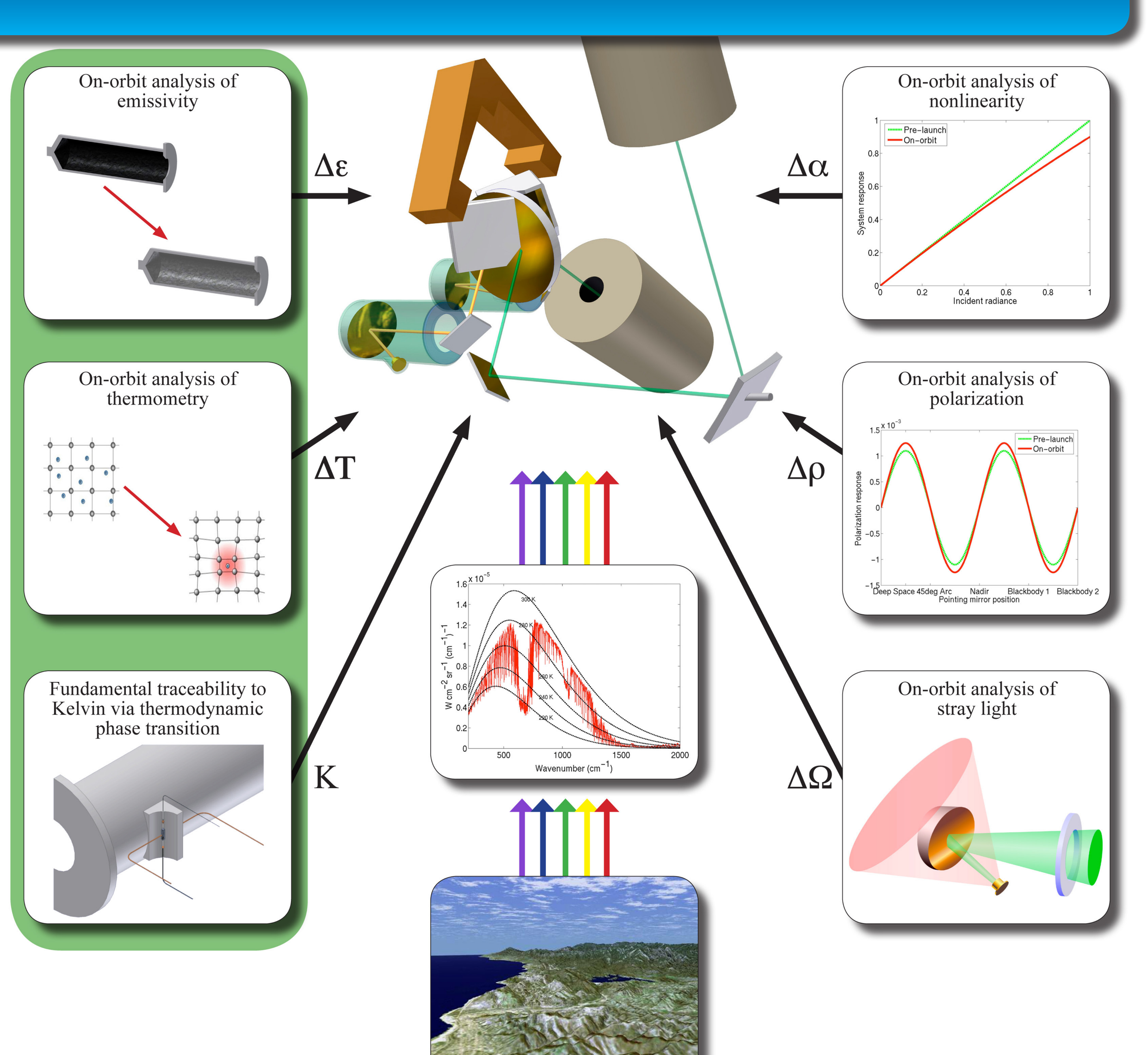



**Fig. 6.** Change in total combined instrument uncertainty arising from a drift in cavity emissivity. The horizontal axis indicates the magnitude of uncorrected drift in cavity effective emissivity from an initial value of 0.999, for a cavity operating at 330 K. The combined uncertainty estimate is comprised of the root sum of squares errors from an estimate of the system-level error budget of a proposed high-accuracy infrared spectrometer satellite instrument[1,9], which includes errors from thermometry, blackbodies, stray light, polarization, detector chain nonlinearity, as well as emissivity drift. The red vertical line represents the uncertainty of emissivity measurement achieved in the current experiment, and shows that the detection limit of the blackbody emissivity diagnostic is well below the current accuracies of infrared sounders.

Condensed from Gero, P. J., J. A. Dykema, and J. G. Anderson, 2008: A quantum cascade laser based reflectometer for on-orbit blackbody cavity monitoring. Submitted to *J. Atmos. Oceanic Technol.*

## On-orbit diagnostics for component uncertainties




## Summary

A phase change measurement and a reflectometer was implemented *in situ* within an infrared spectrometer instrument, and was used to evaluate the temperature and emissivity of an infrared blackbody. Thermometry accurate to 5 mK and emissivity measurements within 1.8 × 10$^{-4}$ were demonstrated. The design is evolvable into a lightweight flight version. High-accuracy, SI-traceable measurements of infrared radiance necessitate that a full instrument component error budget be determined on-orbit, including errors arising from detector signal-chain nonlinearity, polarization, stray light, as well as blackbody temperature and emissivity[10]. The implementation of these diagnostics on an Earth-observing infrared satellite instrument can improve the accuracy of measurement of spectral infrared radiance, and form the basis of more credible observations of climate change.

## References

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